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A FLIGHT STUDY OF THE USE
OF DIRECT-LIFT-CONTROL FLAPS
TO IMPROVE STATION KEEPING
DURING IN-FLIGHT REFUELING

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SYMBOLS

a_N	normal acceleration, g units
F_S	longitudinal stick force, positive aft, N
R_1	range, fuel probe tip to drogue basket, during phase 1, m
R_2	range, fuel probe tip to boom-drogue knuckle, during phase 2, m
α	angle of attack, rad
δ_f	<i>DLC</i> flap (symmetrical aileron) deflection, deg
δ_H	horizontal stabilizer deflection, positive for trailing edge down, deg
δ_S	longitudinal stick deflection, positive aft, cm
ϵ_Y	horizontal station-keeping error in body-fixed axes, positive for fuel probe tip to right of reference, m
ϵ_Z	vertical station-keeping error in body-fixed axes, positive for fuel probe tip above reference, m
ζ_{SP}	short-period mode damping ratio
θ	pitch attitude, positive nose up, deg
$\dot{\theta}$	pitch angular velocity, positive nose up, deg/sec
σ	standard deviation
ω_{SP}	short-period mode natural frequency, rad/sec

Subscripts and Abbreviations

<i>DLC</i>	direct-lift control
<i>IC</i>	DLC to stabilizer interconnect
<i>PD</i>	pitch damper

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SUMMARY

To investigate the effectiveness of fast-acting flaps as direct-lift-control (*DLC*) devices on a fighter airplane, the aileron servo systems of an F-100C variable-stability airplane were modified to provide symmetrical actuation of the surfaces. Initial flight tests using *DLC* indicated that the task of formation flying and, hence, in-flight refueling could be eased by actuating the *DLC* flaps through the conventional control stick, with the degree of improvement depending on the basic stability of the receiver aircraft. Results of refueling approaches and connections with U. S. Air Force tankers indicated a moderate overall improvement in vertical station-keeping performance (approximately 19 percent) and a sizable overall decrease in receiver airplane motions and control activity (approximately 40 percent) with *DLC*.

INTRODUCTION

Direct-lift control (*DLC*), either in the form of spoilers or fast-acting flaps, appears to be an effective means of improving longitudinal flight-path control by uncoupling the pitch and normal-acceleration degrees of freedom. Several applications of *DLC* in both the low and intermediate speed regimes have been treated analytically and in simulator or flight tests by others (refs. 1 through 9).

Two tasks that are basically related — formation flying and in-flight refueling — have been identified as areas in which fighter aircraft might benefit from *DLC*. To determine the utility of the concept, exploratory flight studies were conducted with an F-100C variable-stability airplane. Relatively simple modifications were made to the aileron servo systems of the airplane which enabled the ailerons to be driven symmetrically as flaps as well as differentially for roll control.

Initial flight tests indicated that, for an airplane with low pitch damping, the pilot's control task of vertical station keeping during formation flying could be eased significantly with this form of *DLC*. It was inferred from these initial tests that considerable benefit might result from the use of such a mode of control in the receiver aircraft during in-flight refueling. Accordingly, with the cooperation of the U. S. Air Force, additional tests were conducted in which refueling approaches and connections were made with KC-135 tankers.¹ This report presents and discusses the results of these refueling tests.

¹ The valuable assistance provided by Tactical Air Command, Strategic Air Command, and the Twelfth and Fifteenth Air Forces, USAF, is gratefully acknowledged.

EQUIPMENT AND INSTRUMENTATION

F-100C Variable-Stability Airplane

The F-100C airplane was modified at the Ames Research Center as a variable-stability research vehicle that provides variation of parameters about all three axes. Figure 1 is a photograph of this airplane showing the fuel probe used in the refueling tests. A description of the variable-stability systems is given in the appendix.

Refueling System

The in-flight refueling system consisted of standard probe and drogue hardware used in U. S. Air Force F-100 refueling operations.

Receiver airplane probe— The probe, with nozzle attached at the tip, was mounted beneath the right wing of the F-100C test airplane (fig. 2). For the present tests, the probe was not connected to the F-100C fuel system and therefore it could not take on fuel.

Tanker boom and drogue— The Air Force tankers were KC-135 tankers equipped with flying booms modified for the probe-and-drogue method of refueling. The system is shown, with the important dimensions, in figure 3. For F-100 refueling operations, the length of hose connecting the boom tip and the drogue basket assembly was approximately 2.7 m (9 ft). The boom depression angle was approximately 35° below the tanker fuselage reference and $\pm 15^\circ$ of azimuth adjustment was available. Once the depression and azimuth angles were set by the boom operator, they were not varied during the approach and refueling process. The maximum diameter of the basket lip was 0.6 m (24 in.)

Instrumentation

On-board cameras— The variations in flight path of the test airplane, with respect to given reference points on the tanker boom-drogue system, were recorded by means of two 16-mm motion-picture cameras (Milliken model DBM-5B) operating at 16 frames/sec and located as shown in figure 4. Lenses with a focal length of 10 mm (wide angle) were used to obtain the fields of view indicated in figure 5.

Recording oscillograph— The following airplane flight variables were recorded on a 26-channel photographic oscillograph: pitch angle, roll angle, pitch rate, angle of attack, sideslip, normal acceleration, longitudinal stick position, longitudinal stick force, lateral stick position, rudder pedal position, horizontal stabilizer position, left and right aileron positions, rudder position, static pressure (altitude), and differential pressure (airspeed). Only a few important variables were selected for presentation in time-history form later in the report. The remaining channels were used for recording variable-stability system parameters, which are not included in the above list.

TESTS

Description of the Refueling Task

The task of refueling F-100 aircraft in flight is normally divided into the following steps: (1) lateral transition from the formation of waiting receiver aircraft to the “ready” position — approximately 15 to 23 m (50 to 75 ft) behind the tanker drogue; (2) transition to “precontact” position — approximately 3 to 5 m (10 to 16 ft) behind the drogue; (3) closure to contact (whereupon a light signals “contact” to the tanker co-pilot and fuel transfer is normally begun); (4) transition to receiving position and precision formation flight during fuel transfer; and (5) transition to disconnect position (same position as for initial contact), disconnect, and breakaway.

The receiver pilots are trained to use certain visual cues to establish and maintain airplane position relative to the tanker during refueling. First, three parallel lines painted longitudinally on the underside of the tanker fuselage help the receiver to position his airplane laterally in the “ready” position. Vertical position is established by the apparent position of the fuel hose axis relative to the receiver aircraft nose. This sight picture is maintained as closure is made to the precontact position. During final closure to contact, the pilot focuses primarily on the tanker and boom and only peripheral vision is used to check the probe-to-drogue relationship.

After contact, the hose is slackened to prevent whipping while receiving fuel. This hose deformation is accomplished by altering the receiver aircraft position so that the drogue is moved approximately 1 ft to the left and 1 ft above its free trailing position. The variable-stability F-100C in the proper fuel-receiving position is shown in figure 6. The receiving position is maintained visually by keeping the “knuckle” (the assembly at the end of the tanker boom to which the hose is attached) in the lower aft corner of the right-hand windshield panel. A very tight tracking task is required to hold this position. When the fuel has been transferred, the drogue is returned to its free trailing position and engine thrust is decreased slightly to withdraw the probe.

Variable-Stability Test Configurations

To investigate the effects of *DLC* in comparison with a more conventional method of stabilization (in this case, a pitch damper), the following three combinations of system variables were used in the F-100C tests.

Configuration I— Variable-stability systems are engaged with fly-by-wire control about all three axes; there is no pitch damper or *DLC* ($\xi_{SP} = 0.22$).

Configuration II— Same as configuration I, but with substantial pitch-rate damping augmentation ($\xi_{SP} = 0.75$).

Configuration III— Same as configuration I, but with *DLC* characteristics (flap deflection per unit longitudinal stick deflection and horizontal stabilizer interconnect ratio) optimized empirically for precision formation flying. The low damping ratio of 0.22 for configuration I was the natural damping ratio of the unaugmented airplane and served as a useful reference configuration to demonstrate the benefits of *DLC*.

The system parameters associated with each configuration are given in table 1.

Pilots

Two NASA research pilots participated in the refueling tests. Each pilot had military experience in fighter and single-engine attack aircraft, which included probe-and-drogue refueling operations in A-4 aircraft. Pilot A had recent aerial refueling experience, but pilot B (although a more experienced pilot) had not performed aerial refueling recently. While both pilots were experienced in the F-100C, neither had refueled that type of aircraft in flight before the tests. The two pilots were given approximately 4 hours of ground instruction by U. S. Air Force personnel before the first refueling flight.

Test Procedure

The refueling tests consisted in making repeated closures and connections with the tanker, each time maintaining contact for a length of time representative of that required for fuel transfer. For each receiver airplane configuration, the pilots commented on characteristics pertaining to ease and performance of the task. Items considered were: pitch attitude changes required for vertical positioning, vertical translation sensitivity to longitudinal stick inputs, ease of vertical positioning, stick forces required, pitch damping, static longitudinal stability, and general characteristics such as longitudinal response to thrust control and lateral-directional behavior. A pilot rating number, according to the early Cooper scale shown in table 2, was assigned to each configuration for the overall refueling task.

For purposes of analysis, each refueling run was divided into two phases: phase 1 comprised the approach to contact and phase 2 was that portion of the run during which the probe and drogue were connected.

RESULTS AND DISCUSSION

Refueling Tests

Figure 7 presents time histories of ranges R_1 and R_2 , horizontal tracking error ϵ_Y , vertical error ϵ_Z , and airplane motions during two refueling runs for configurations I and III. Both phase 1 (approach) and phase 2 (connected) are shown. The discontinuities in the time histories of R , ϵ_Y , and ϵ_Z between phases 1 and 2 occurred as a result of shifting the error reference from the center of the drogue, at its maximum diameter, to the center of the retainer assembly (knuckle).

The example in figure 7(a) is an extreme case in which considerable difficulty was encountered with configuration I (no augmented pitch damping, no *DLC*), particularly in phase 2. The example in figure 7(b) is typical of configuration III, characterized by improved tracking and greatly decreased airplane motions.

Tracking performance— The level of performance of each pilot in tracking during the refueling task is presented in bar-graph form in figure 8 and numerically in table 3 for configurations I, II, and III. The indicated levels of standard deviation σ_{ϵ_Y} and σ_{ϵ_Z} for each case represent average values computed for a number of runs, weighted according to run length.

If there was any improvement in tracking due to the addition of pitch damping or *DLC* it would be evident mainly in the vertical component ϵ_Z . Figure 8 shows, for pilot B in phases 1 and 2 and pilot A in phase 1, a progressive (but not dramatic) decrease in σ_{ϵ_Z} for configurations I, II, and III. The overall improvement in σ_{ϵ_Z} was about 19 percent. For these cases, the simple addition of pitch damping (configuration II) was about as effective as *DLC*. Only the case for pilot A, phase 2 did not show improvement with *DLC*. While there was improvement in the horizontal component σ_{ϵ_Y} with pitch damping or *DLC* for one case (pilot B, phase 1), the remaining results show a random variation, or even a degradation, in performance.

Receiver airplane motions— Figure 9 shows the degree of longitudinal motion of the pilot's controls and of the airplane during the refueling task. These results, given as standard deviations of stick deflection and force, pitch rate, pitch angle, and normal acceleration, are also shown numerically in table 4.

The improvement in tracking performance noted with the addition of pitch damping or *DLC* is reflected in a general way in the motions. In fact, on the basis of percentage of pitching and normal acceleration amplitudes, greater improvement was apparent in terms of reduction of airplane motions, about 40 percent overall, than would be inferred from the corresponding decreases in vertical tracking error. These reductions in motion undoubtedly had a favorable effect on pilot opinion (to be discussed later). With pitch damping or *DLC*, both pilots were able to reduce the airplane motions to about the same small amplitudes.

Pilot comments and ratings— The pilot comments and ratings given for configurations I, II, and III are presented in table 5. Both pilots noted a definite improvement in configurations II and III over configuration I in ease of making vertical corrections as well as an increase in apparent pitch damping of the airplane. Little difference between configurations II (added pitch damping) and III (with *DLC*) was noted in the response of the airplane; however, pilot A remarked that configuration III was slightly superior. This observation was in general agreement with the standard deviations of errors and motions (figs. 8 and 9). These comments are reflected in the numerical ratings in table 5. which show an improvement with *DLC* of 1-1/2 rating points for pilot A and 2 points for pilot B.

Further observations— In configuration II, any pitch oscillations were damped rapidly by providing pitch rate feedback to the stabilizer. In configuration III, *DLC* apparently provided sufficient (though not complete) uncoupling of the pitch and vertical-translation degrees of freedom so that significant pitch oscillations were not initially excited.

Although the results of this study indicate significant decreases in vertical tracking error and airplane motions, there appears to be little difference whether these improvements were obtained

through pitch damping augmentation or *DLC*. A decision as to which method to use in a given application could then depend on considerations such as ease of mechanization and system reliability

CONCLUSIONS

From a flight investigation of *DLC* during in-flight refueling, with a variable-stability F-100C airplane, the following conclusions are drawn:

1. Use of *DLC* resulted in improved station keeping during in-flight refueling. The overall improvement in vertical error was approximately 19 percent and the overall decrease in receiver airplane motions and control inputs was approximately 40 percent.
2. The addition of pitch rate damping, without *DLC*, resulted in nearly the improvement seen with *DLC*.
3. Based largely on ease of performance, the use of *DLC* in the in-flight refueling task resulted in a pilot-rating improvement of 1-1/2 to 2 rating points over the basic airplane. This improvement, considering the average ratings of the two pilots, was sufficient to cross the 3-1/2 rating boundary from unsatisfactory to satisfactory.

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Moffett Field, Calif. 94035, August 17, 1973

APPENDIX

DESCRIPTION OF THE VARIABLE-STABILITY SYSTEMS

GENERAL

Variable-stability capability about three axes was provided in the F-100C test airplane through mechanical and electrical modification of the flight-control systems as response-feedback, variable-stability systems having pilot-selected gains. The mechanical modifications were relatively straightforward because the normal F-100C flight-control systems were irreversible hydraulic systems with artificial feel. Variable stability was provided by sensing angle of attack, sideslip, and airplane angular rates by means of electrical transducers, summing them, then using the amplified signals to drive the hydraulic valves to the control surface actuators. The signal summing amplifiers and servo amplifiers were 400-Hz AC units. The signs of the response feedback gains were determined by setting the individual signals to be in phase or 180° out of phase. To avoid motion feedback to the pilot's controls, it was necessary to break the mechanical connections to the cockpit controls and insert disconnect linkages. During variable-stability operation, the pilot control inputs were introduced electrically in a "fly-by-wire" fashion. The amount of variable-stability servo authority was determined by the amount of mechanical free play in the disconnect linkages, which was adjustable in the pitch and roll systems. Reversion to the normal hydromechanical mode of control was quickly achieved by mechanically closing the disconnect linkages through pilot actuation of a thumb button or switch in the cockpit.

Figure 10 is a block diagram of the variable-stability systems.

YAW AND ROLL VARIABLE-STABILITY SYSTEMS

The yaw and roll variable-stability systems were essentially the same in concept. Both systems used geared servo motors that drove the normal actuator valves through slip clutches.

In the roll system, separate and independent servo loops were provided, with common input command signals. Because of this feature, it was relatively easy (by means of simple additions to the command circuits) to provide symmetrical aileron movement as *DLC* flaps and yet retain their normal function as roll control devices.

PITCH VARIABLE-STABILITY SYSTEM

The pitch variable-stability system differed from the systems in the other axes in its requirements for flight safety, which were brought about by the presence of an all-moving horizontal tail. To minimize the possibility of a hard-over failure, the following authority restrictions were imposed: (1) a fixed, pilot-adjustable limit up to $\pm 5^\circ$ of the surface deflection

about trim, provided both mechanically and as a limit on the variable-stability drive signal and (2) a modulated authority limit in the disconnect unit, controlled by the variable-stability drive signal, which automatically restricted the authority at any instant to just slightly more than the surface deflection then being commanded.

In addition to the above limits, the pitch system reverted automatically to the basic mechanical mode of control if the aircraft normal acceleration exceeded certain limits selectable by the pilot. Other system abnormalities that could trigger the same action were loss of electrical power, loss of hydraulic pressure or fluid, abnormal power supply voltage, or excessive servo error signal.

Other mechanical features of the stabilizer variable-stability system are explained in reference 10.

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TABLE 1.— SYSTEM AND AIRPLANE RESPONSE PARAMETERS FOR THE
CONFIGURATIONS TESTED

Parameter	Configuration		
	I	II	III
Variable—stability system	Engaged	Engaged	Engaged
$(\delta_f / \delta_s)_{DLC}$, deg/cm (deg/in.)	0	0	1.71 (4.34)
$(\delta_H / \delta_f)_{IC}$	0	0	— .24
$(\delta_H / \dot{\theta})_{PD}$, sec	0	.22	0
F_s / a_N , N/g (lb/g)	56.0 (12.6)	79.2 (17.8)	60.1 (13.5)
a_N / α , g/rad	16.6	16.6	21.2
ω_{SP} , rad/sec	2.8	3.2	2.8
ζ_{SP}	.22	.75	.22

TABLE 2.- PILOTS' RATING SCHEDULE

Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

TABLE 3.— STANDARD DEVIATIONS OF HORIZONTAL AND VERTICAL STATION—
KEEPING ERRORS DURING IN-FLIGHT REFUELING

Pilot	Variable	Phase 1			Phase 2		
		Configuration			Configuration		
		I	II	III	I	II	III
A	σ_{ϵ_Y} , m (ft)	0.21 (0.70)	0.13 (0.44)	0.25 (0.83)	0.14 (0.46)	0.20 (0.66)	0.19 (0.61)
	σ_{ϵ_Z} , m (ft)	.26 (.85)	.22 (.72)	.21 (.68)	.26 (.85)	.23 (.74)	.27 (.89)
B	σ_{ϵ_Y} , m (ft)	.32 (1.06)	.22 (.71)	.19 (.61)	.41 (1.34)	.30 (.98)	.46 (1.50)
	σ_{ϵ_Z} , m (ft)	.28 (.92)	.20 (.65)	.18 (.60)	.31 (1.03)	.25 (.82)	.23 (.77)

TABLE 4.— STANDARD DEVIATIONS OF RECEIVER AIRPLANE CONTROL INPUTS AND
MOTIONS DURING INFLIGHT REFUELING

Pilot	Variable	Phase 1			Phase 2		
		Configuration			Configuration		
		I	II	III	I	II	III
A	δ_s , (in.)	0.23 (0.09)	0.25 (0.10)	0.18 (0.07)	0.33 (0.13)	0.28 (0.11)	0.30 (0.12)
	F_s , (lb)	5.69 (1.28)	5.87 (1.32)	5.20 (1.17)	6.81 (1.53)	5.83 (1.31)	6.63 (1.49)
	$\dot{\theta}$, deg/sec	.63	.37	.33	1.00	.40	.59
	θ , deg	.23	.15	.16	.36	.19	.30
	a_N , g	.08	.04	.04	.11	.05	.07
B	δ_s , (in.)	.33 (.13)	.18 (.07)	.20 (.08)	.58 (.23)	.25 (.10)	.25 (.10)
	F_s , (lb)	8.50 (1.91)	7.12 (1.60)	5.65 (1.27)	9.03 (2.03)	6.94 (1.56)	8.10 (1.82)
	$\dot{\theta}$, deg/sec	1.09	.35	.37	2.21	.46	.67
	θ , deg	.39	.13	.11	.74	.23	.33
	a_N , g	.11	.04	.04	.24	.05	.08

TABLE 5.— PILOT RATINGS AND SUMMARY COMMENTS

Pilot	Configuration	Pilot rating	Comments
A	I	4-1/2 - 5	Lack of sufficient pitch damping caused some overcontrolling unless pilot used tighter control. Ease of vertical positioning was considered poor. The aircraft was less steady than in configurations II and III and it was obvious that precise control was more difficult and required more concentration and effort.
	II	3-1/2 - 4	Pitch damping was satisfactory. Ease of vertical positioning was fair. Control response was quite smooth.
	III	3 - 3-1/2	Pitch damping was satisfactory. Ease of vertical positioning was good, a little better than in configuration II. It was difficult to see any significant difference between pitch response of configurations II and III. Pure vertical translation, with absence of pitch attitude change, was not observed.
	General		Normally, only very small pitch inputs were required for the refueling task. Other major factors which determined success of the refueling task were depth perception, establishment of proper "sight picture", longitudinal response to throttle movement, and lateral translation. In all three configurations, static longitudinal stability was fair and longitudinal stick forces required were satisfactory. Lateral-directional response characteristics were satisfactory.
B	I	4-1/2	Pretty bad at first, with considerable oscillating and overcontrolling in pitch, particularly when trying to fly with reference to the basket. Pitch oscillations were too lightly damped. Ease of vertical positioning was poor; sensitivity to longitudinal stick inputs appeared too great. I finally effected a connection after switching my reference to the knuckle at the end of the boom. Trying to maintain position after connection again resulted in severe pitch oscillations and very high pilot work load.
	II	2-1/2	Very similar to configuration III. I could not really say that I could see any difference between II and III. Pitch damping was satisfactory. Ease of vertical positioning was good; sensitivity to longitudinal stick input was satisfactory.
	III	2-1/2	The first series of connections was made with this configuration. Vertical positioning was pretty good; sensitivity to stick input was satisfactory. Pitch damping was satisfactory. I could fly pretty well by referring to the basket itself. After connection, I could maintain vertical and horizontal position fairly well, but longitudinal positioning was a problem (as with the other two configurations) and some inadvertent disconnects occurred. As experience was gained, I was able to improve longitudinal positioning through tighter thrust control.
	General		Quite a bit of learning was required to develop tightness and proper lead in thrust control for longitudinal positioning. In all three configurations, static longitudinal stability was good and longitudinal stick forces required were satisfactory. Lateral-directional characteristics were considered good.



Figure 1.— F-100C airplane with refueling probe installed.

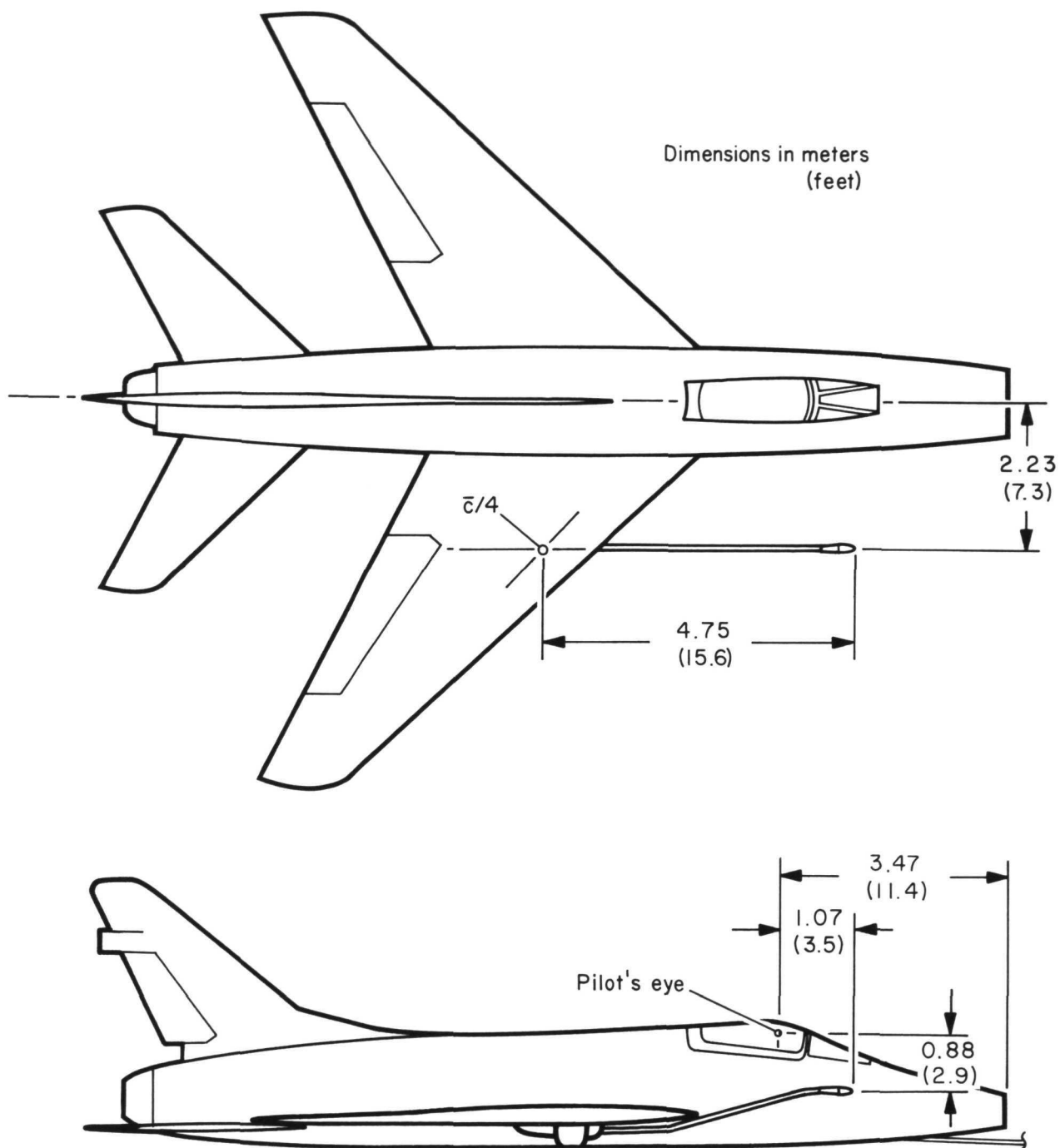


Figure 2.— Principal dimensions of fuel probe installation.

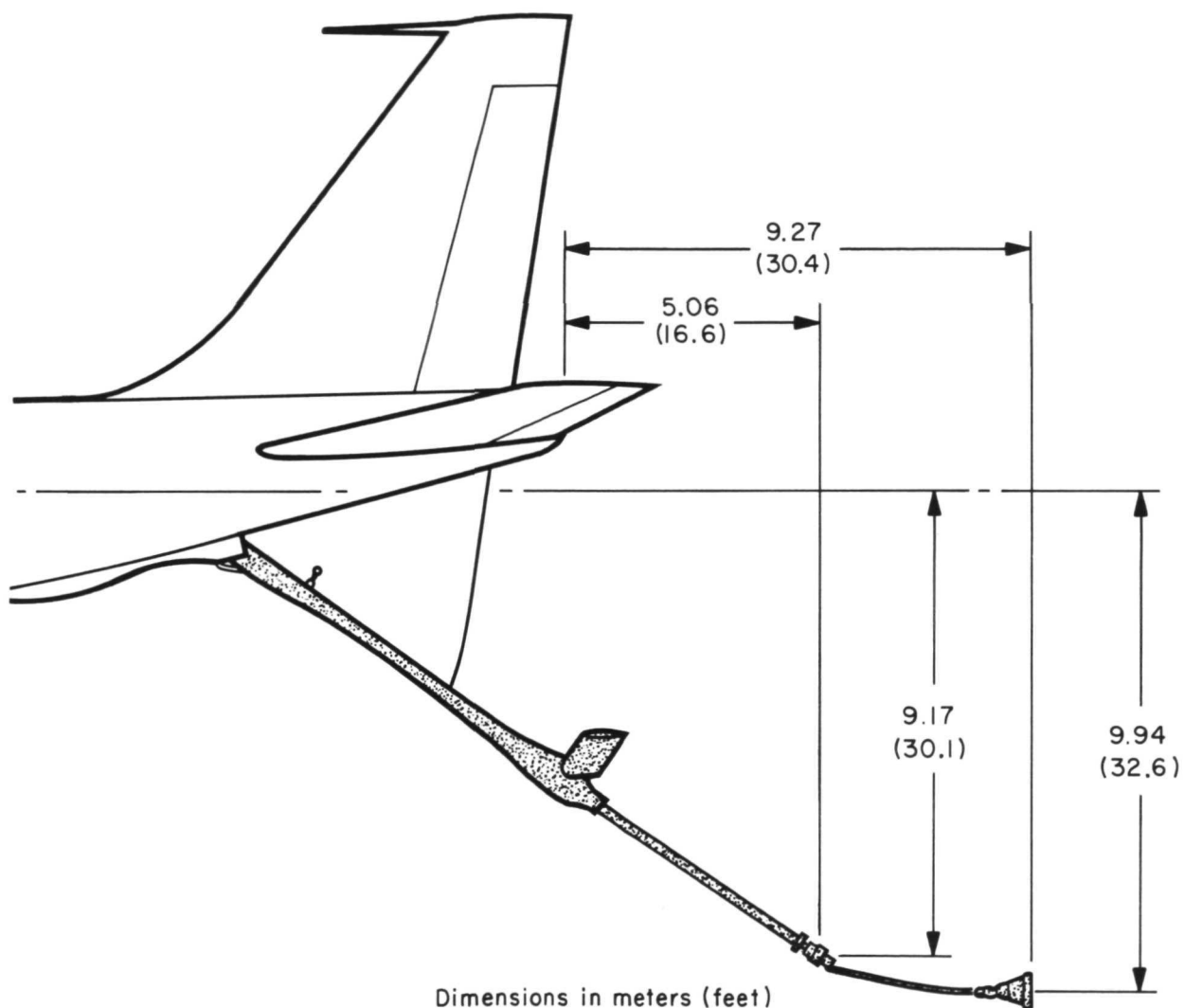


Figure 3.— Principal dimensions of boom-drogue refueling system.

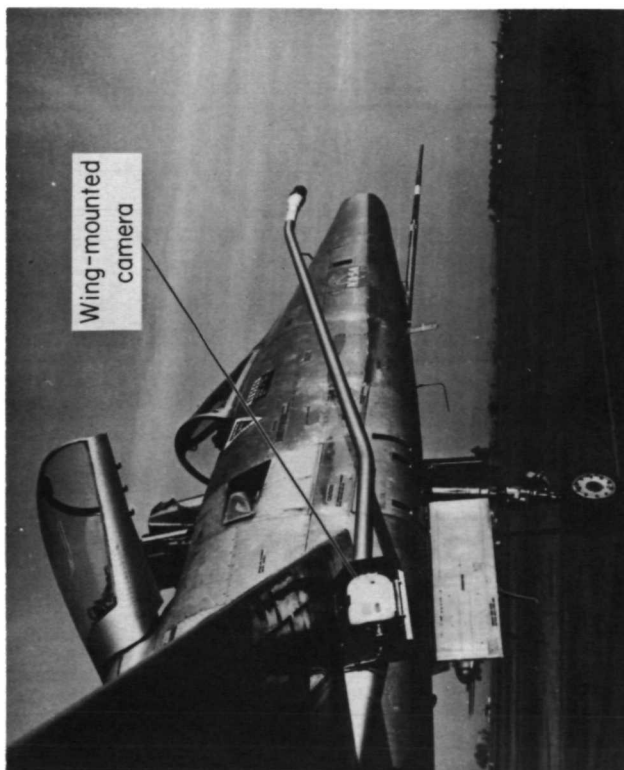
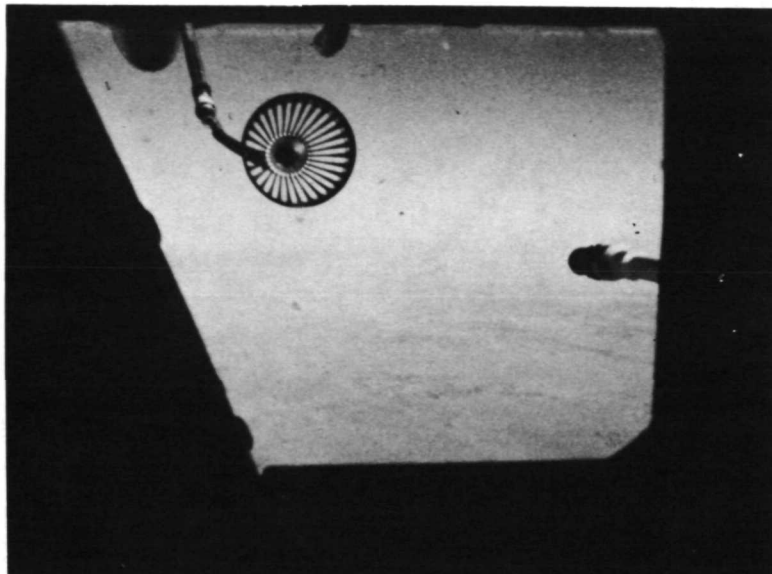


Figure 4.— 16-mm camera installations on F-100C airplane.



Fuselage-mounted camera



Wing-mounted camera

Figure 5.— Fields of view of the 16-mm cameras; $R_1 = 2.35$ m (7.7 ft).

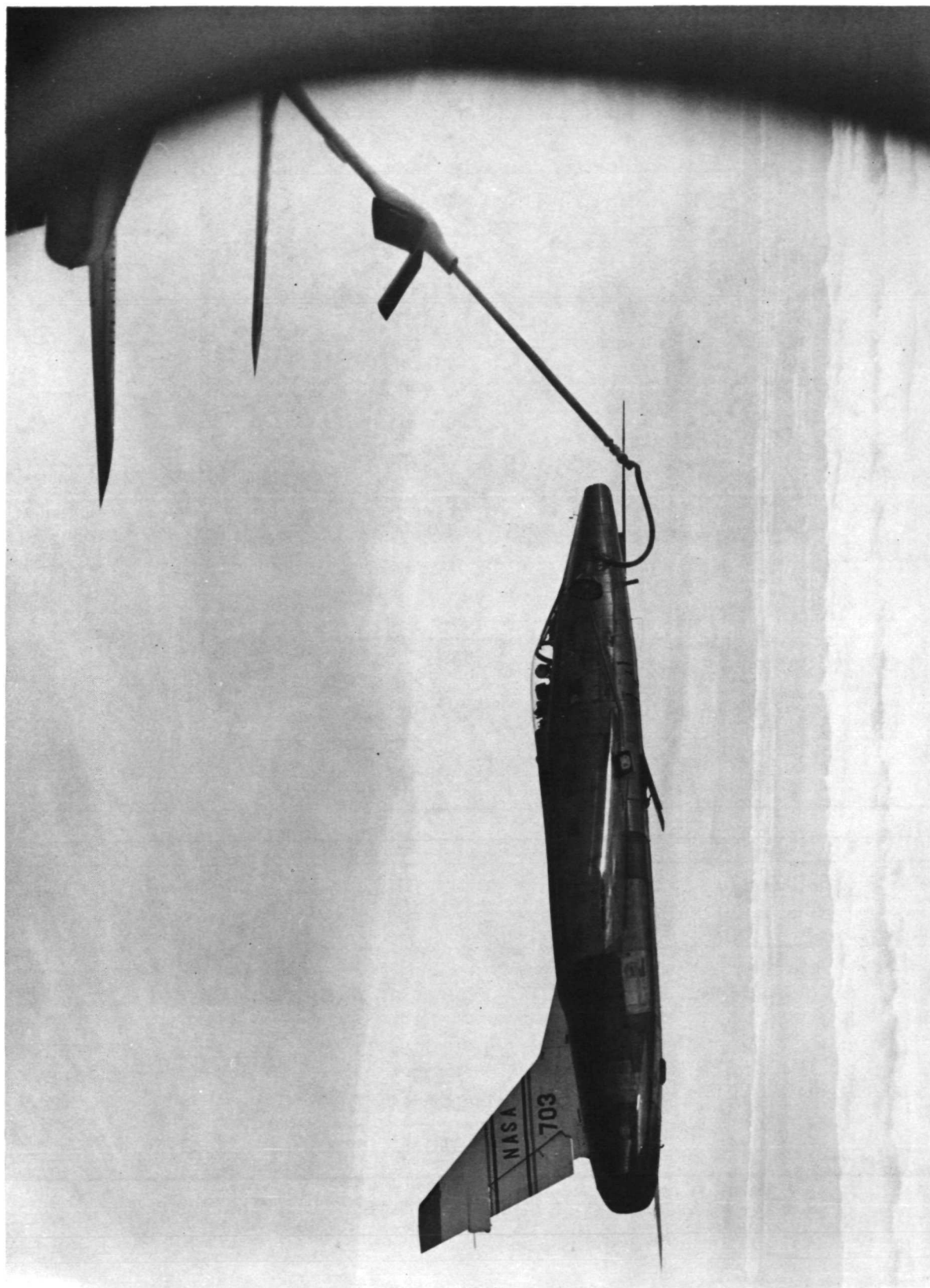
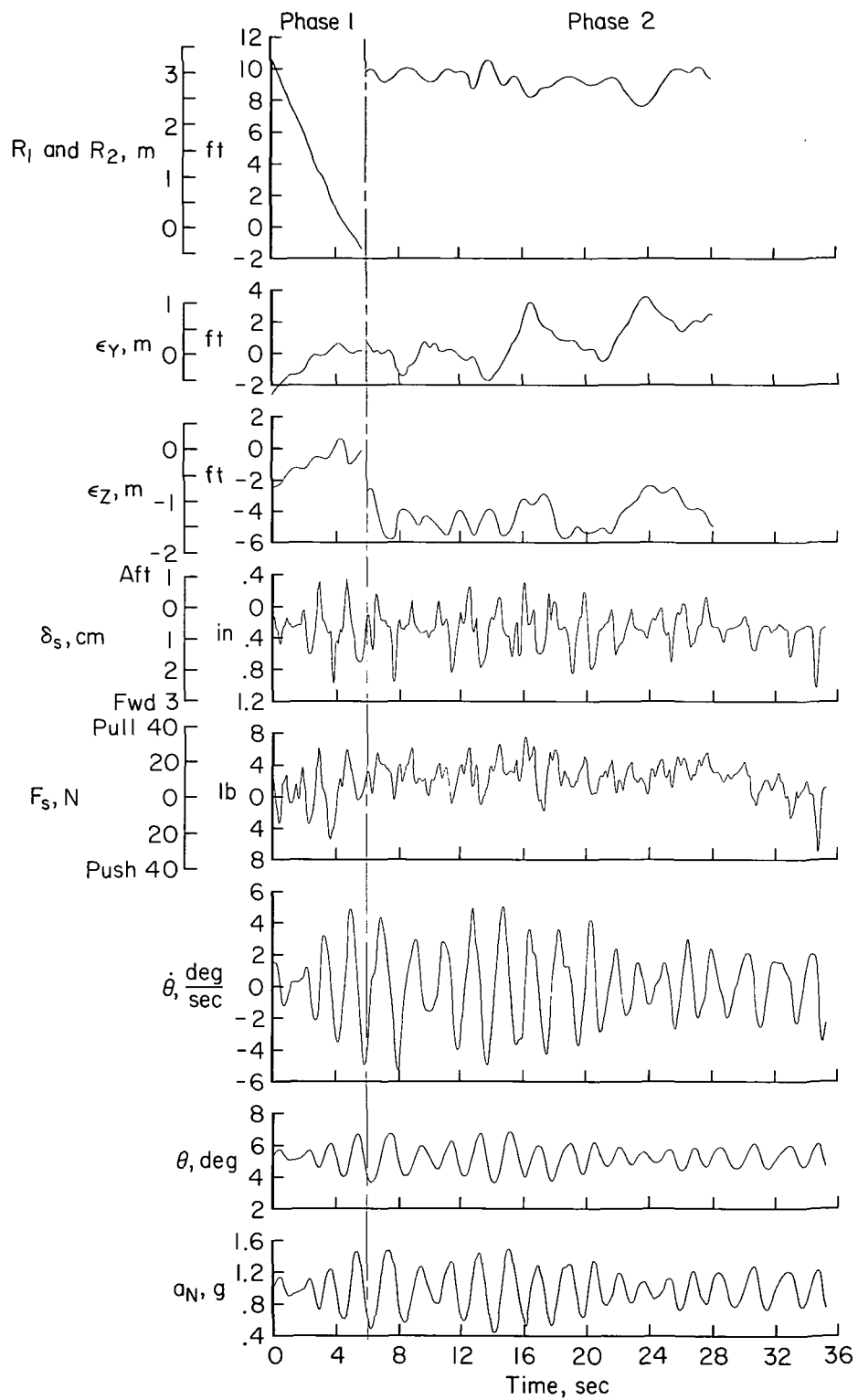
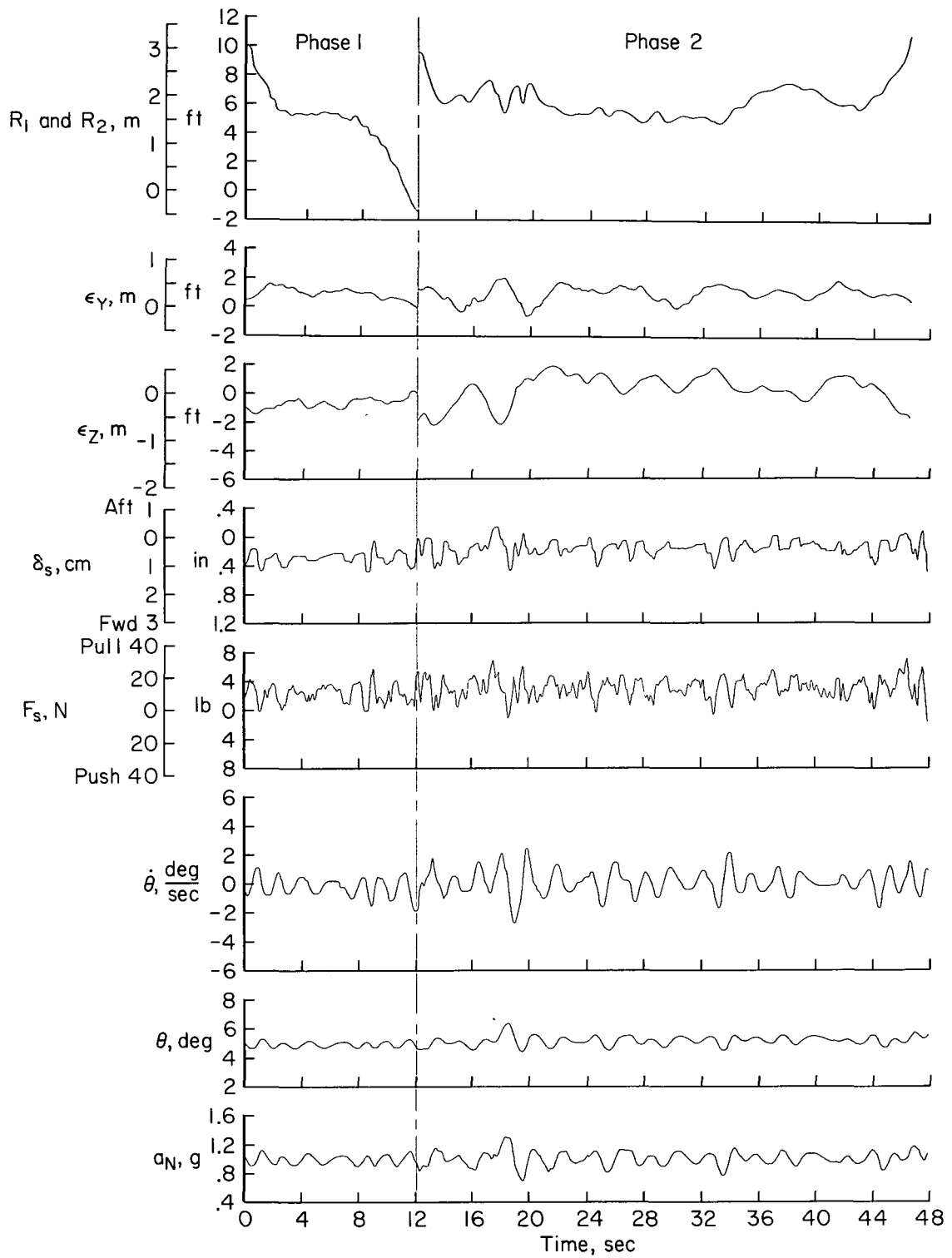


Figure 6. – F-100C in fuel-receiving position.



(a) Configuration I.

Figure 7.— Time histories of refueling runs.



(b) Configuration III.

Figure 7.— Concluded.

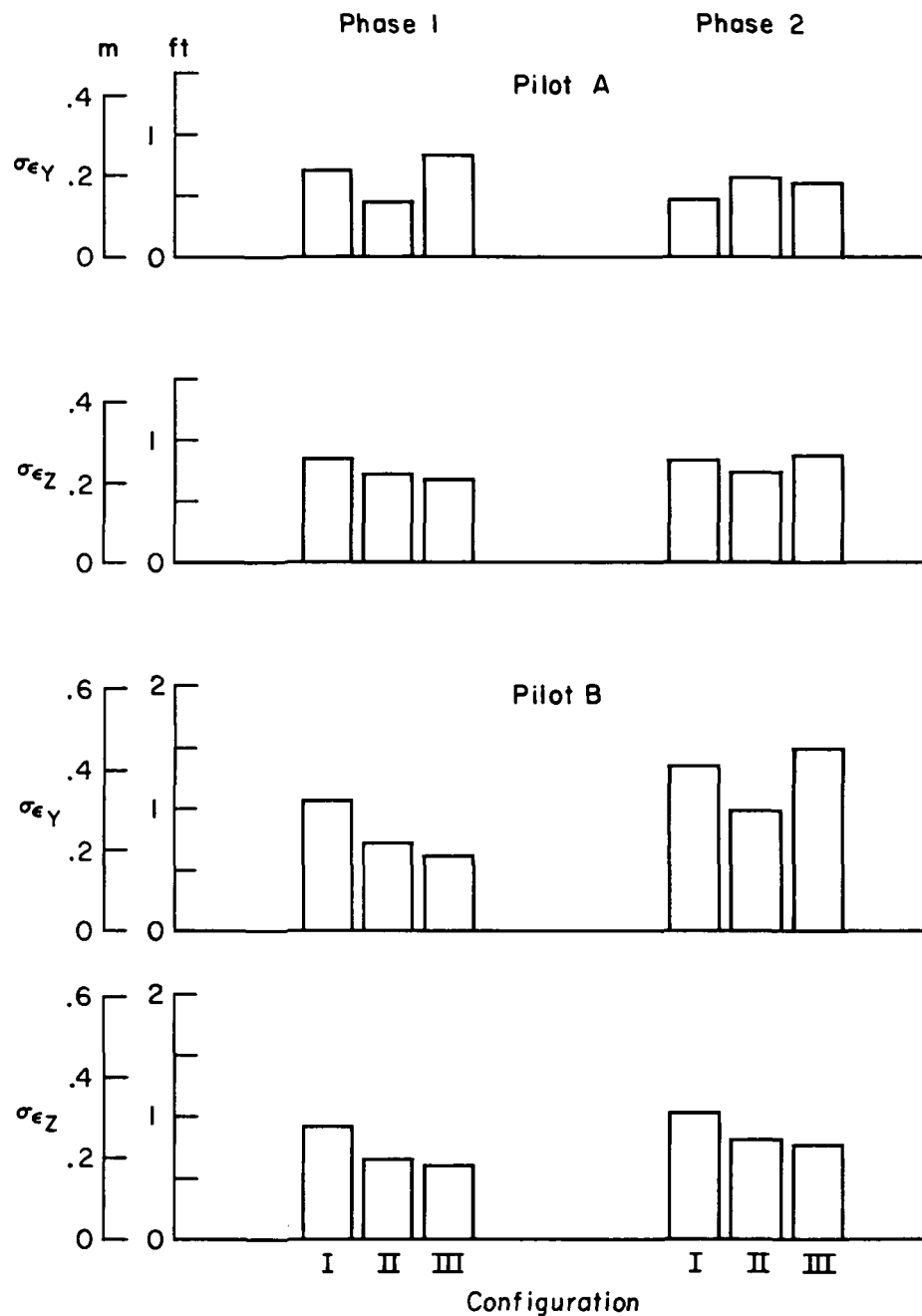


Figure 8.— Standard deviation of tracking errors during phase 1 and phase 2 for receiver airplane configurations I, II, and III.

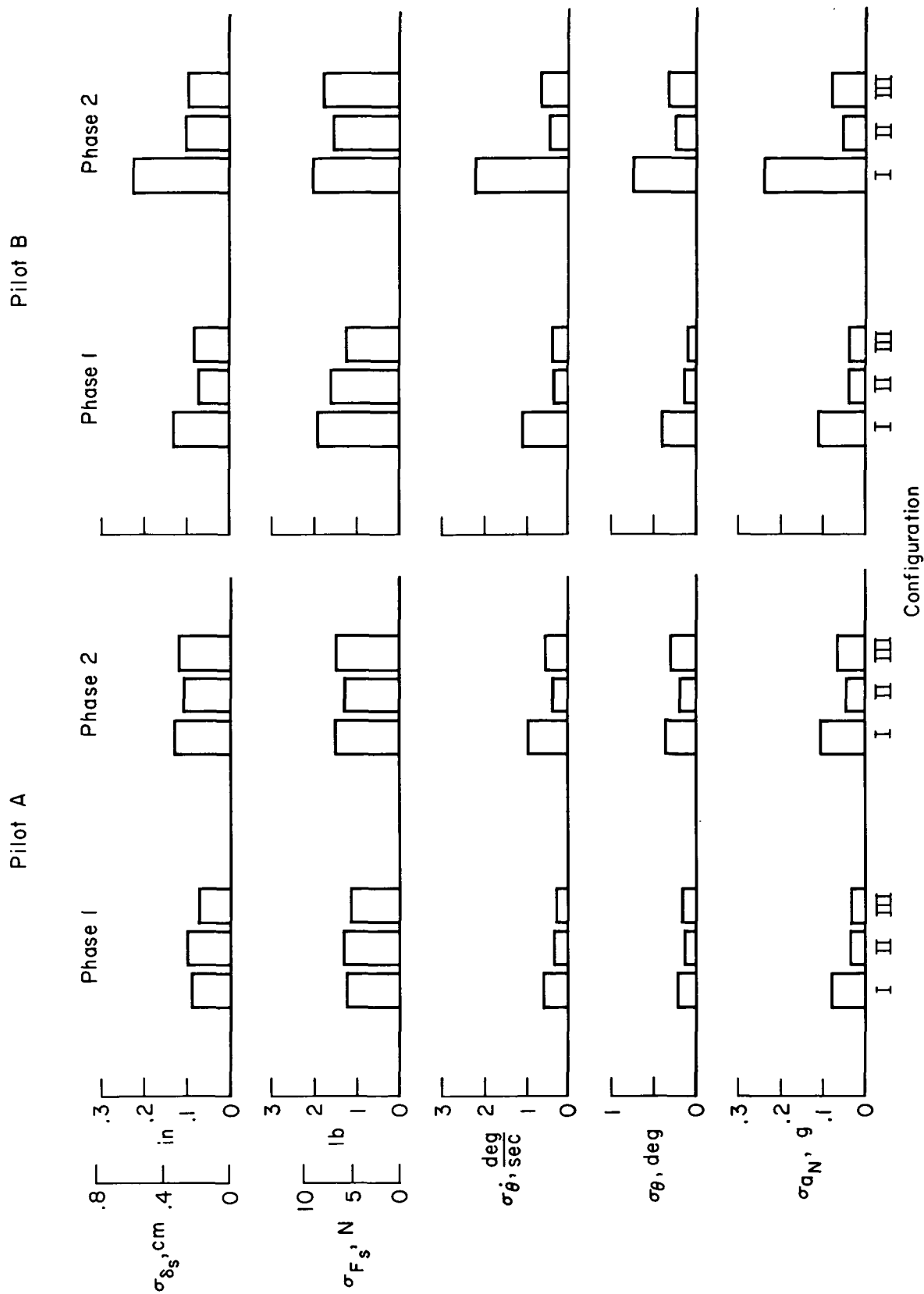


Figure 9. — Standard deviation of receiver airplane control and motion variables during phase 1 and phase 2.

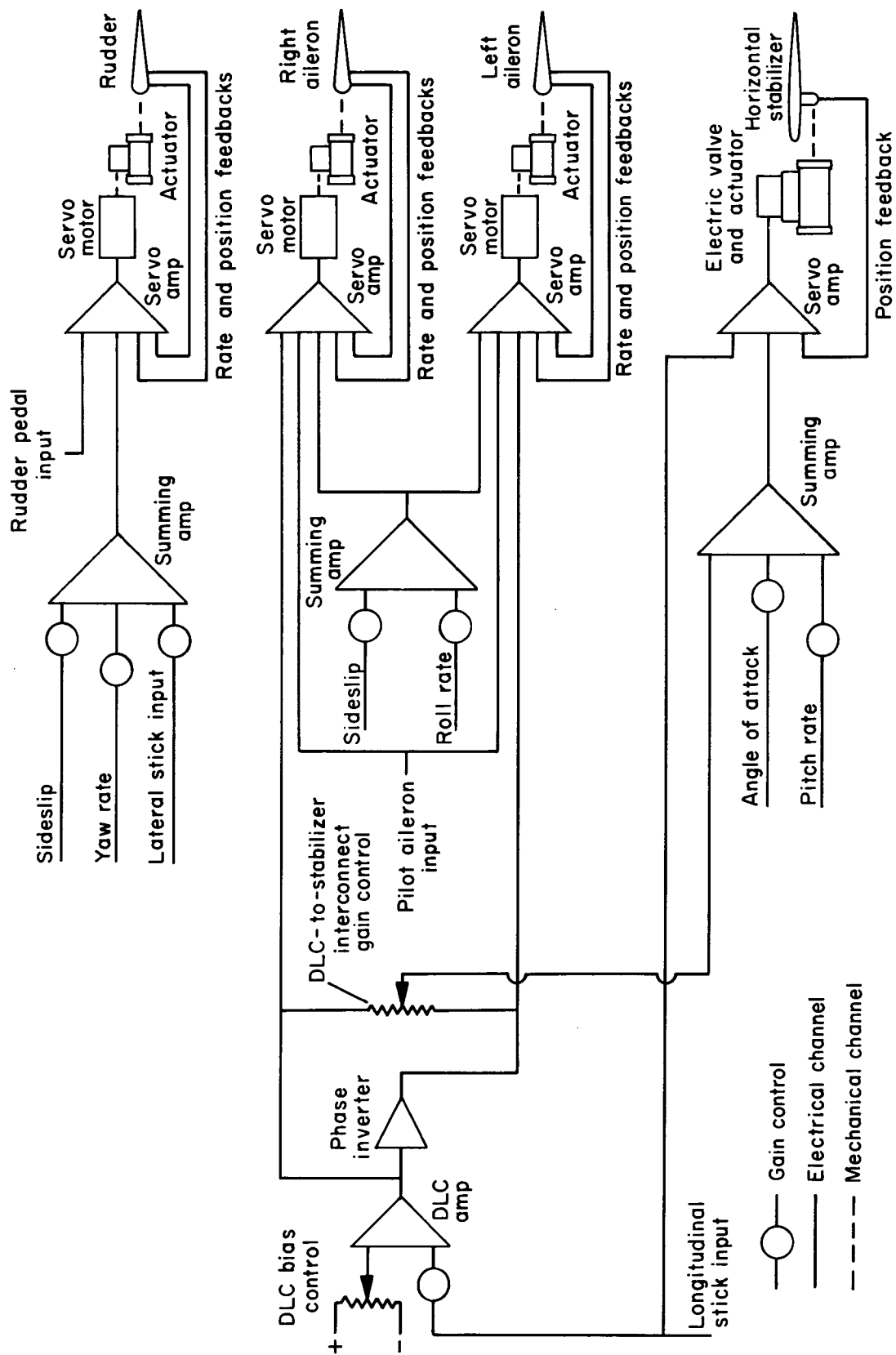


Figure 10.— Simplified block diagram of F-100C variable — stability systems.



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